



Comprehensive Review of Seed-Borne Pathogens: Challenges and Control in Crop Production

**BARKHA KACHHAP¹, SNEHA PANDEY², MAINAK BANERJEE^{3*},
AMIT KUMAR PANDEY⁴ and NILU KUMARI²**

¹ Faculty of Life Sciences, RKDF University, Ranchi, Jharkhand, India.

²Department of Biotechnology, RKDF University, Ranchi, Jharkhand, India.

³Department of Zoology, RKDF University, Ranchi, Jharkhand, India.

⁴Department of Microbiology, RKDF University, Ranchi, Jharkhand, India.

Abstract

Seed-borne diseases pose a significant threat to agriculture by affecting the seed quality, germination, and crop yield. This review examines how seed-borne pathogens including fungi, bacteria, viruses, and nematodes affect agricultural productivity and food security. The mechanisms of transmission and infection were analyzed, focusing on vertical transmission and seed microbiome dynamics. The factors affecting disease prevalence, including environmental conditions and seed storage practices, were examined. The review assessed the effects of seed treatment on crop productivity and yield, emphasizing the importance of seed health. Methods for detecting seed-borne pathogens, including visual inspection, blotter tests, and PCR-based techniques, are presented. Seed health testing and certification of global trade requirements are also highlighted. This review addresses the challenges in managing these diseases, including novel pathogens and climate change impacts. A comprehensive strategy incorporating technological innovations and enhanced regulations is required for sustainable crop production.



Article History

Received: 08 July 2025

Accepted: 18 August 2025

Keywords

Crop Productivity;
Detection Methods;
Disease Management;
Food Security;
Seed-Borne Diseases.

Abbreviations

PCR Polymerase Chain Reaction,
TBRV Tomato black ring virus,
RRV Raspberry ringspot virus,
ZYMV Zucchini yellow mosaic virus,
PepMV Pepino mosaic virus,
PDA Potato Dextrose Agar

CONTACT Mainak Banerjee ✉ mainak.bio@gmail.com 📍 Department of Zoology, RKDF University, Ranchi, Jharkhand, India.



© 2025 The Author(s). Published by Enviro Research Publishers.

This is an  Open Access article licensed under a Creative Commons license: Attribution 4.0 International (CC-BY).

Doi: <http://dx.doi.org/10.12944/CARJ.13.2.3>

Introduction

The global population is experiencing rapid growth, presenting a significant challenge to agriculturalists worldwide in terms of ensuring adequate food supply. Seeds are a fundamental and essential input for agriculture, and play a crucial role in achieving global food security. Approximately 90 percent of crops cultivated globally are propagated through seeds.¹ Seed-borne diseases are plant infections caused by pathogens that reside within or on the seed surface.² These diseases significantly affect agriculture by hindering seed germination and seedling growth, ultimately reducing crop yield. Seed-borne pathogens, such as fungi and bacteria, can substantially diminish seed quality and adversely affect crop production by decreasing both the quantity and quality of the output.^{3,4}

The significance of managing seed-borne diseases in agriculture is multi-faceted. First, healthy seeds are essential for successful crop cultivation, as they directly affect the effectiveness of other farming inputs and can boost crop yield by approximately 18–20% when optimized. However, seed-borne pathogens can severely hinder seed germination and diminish seedling vigor, resulting in yield losses ranging from to 15-90% in severe cases.³

Seed-borne diseases play a significant role in the global dissemination of plant pathogens, as infected seeds can transport diseases across regions and even continents, resulting in new outbreaks and impacting biodiversity. Biological control agents and eco-friendly alternatives are being investigated as substitutes for chemical pesticides, which pose environmental hazards and contribute to pathogen resistance.⁵ These biological interventions include the use of endophytes, beneficial microbes that inhabit seeds and suppress harmful pathogens, highlighting their potential to enhance plant resistance and promote growth.^{6,7}

Economic losses can also arise from diminished seed quality, which affects seed marketability.⁸ The seed industry, particularly in commodities such as tomatoes and peppers, consistently grapples with seed-borne bacteria that adversely affect crop yields and profits.⁹ The necessity for extensive chemical treatments to disinfect seeds not only increases agricultural input costs but also raises environmental concerns. These treatments are crucial for managing pathogens,

particularly fungi, and for ensuring sustainable crop production.^{9,10} However, the decreasing effectiveness of chemical treatments against bacterial pathogens presents further challenges, prompting the need for alternative methods such as thermotherapy or biological control.¹⁰

These diseases also influence crop management practices, including reseeded, because of low seed germination or poor seedling emergence rates. This involves significant direct and indirect costs for farmers.¹¹ Therefore, addressing seed-borne diseases is crucial for reducing economic losses and ensuring food security through sustainable agricultural practices. This review aims to explore the significance of seed-borne diseases in agriculture, examining their impact on crop production, global food security, and economic outcomes, while discussing potential management strategies and alternative control methods.

Areas Covered

This review covers the following key areas

- Types and impacts of seed-borne pathogens (fungi, bacteria, viruses, and nematodes) on crop production and food security
- Transmission mechanisms and infection processes of seed-borne diseases
- Factors affecting prevalence of seed-borne diseases (environmental conditions, seed storage practices, crop management)
- Detection and diagnosis methods for seed-borne pathogens (traditional and advanced techniques)
- Management and control strategies (seed treatments, cultural practices, resistant varieties, integrated disease management)
- Effects on seed quality, germination, seedling vigor and crop yields
- Seed health testing and certification for global trade
- Challenges in managing seed-borne diseases (emerging pathogens, climate change impacts, limitations of current methods)

This review work conducted a comprehensive literature review of topics related to seed-borne pathogens and their impact on agriculture. This review examines research on the biology, epidemiology, detection, and management of seed-borne diseases in various crops synthesizes current

knowledge and highlights key issues and future research needs in this field.

Expert Opinion

Seed-borne pathogens pose a significant threat to global agriculture and food security by affecting seed quality, germination rates, and crop yields. These pathogens, including fungi, bacteria, viruses, and nematodes, can cause substantial economic losses, with yield reductions ranging from 15-90% in severe cases. The impact of seed-borne pathogens is multifaceted. Infected seeds often have lower germination rates and produce inferior seedlings, which directly affects crop establishment and yield potential. Moreover, these pathogens can spread to new areas through infected seeds, leading to disease outbreaks across regions and continents, raising major biosecurity concerns in global seed trade. Economic losses extend beyond direct yield reduction. Seed-borne diseases increase production costs through the need for chemical treatments and potential crop failures that require replanting. Heavy reliance on chemical seed treatments also raises environmental concerns and the risk of pathogen resistance development. Climate change further complicates the management of seed-borne pathogens. Shifting weather patterns may alter pathogen distributions and infection dynamics, making the implementation of effective control strategies more challenging. The detection of seed-borne pathogens remains a challenge. Advanced techniques such as PCR and hyperspectral imaging offer improved detection, standardization and cost which remain barriers to their widespread adoption. Additionally, international standards for seed health testing and certification are not fully harmonized, potentially allowing the spread of pathogens through trade. The Effective management of seed-borne pathogens requires an integrated approach. This includes combining cultural practices, resistant varieties, biological controls, and the reasonable use of chemical treatments. The development of novel seed treatments, including biocontrol agents and natural compounds, can provide protection while reducing environmental impacts. Continuous breeding efforts and genetic engineering approaches to develop pathogen-resistant crop varieties are crucial. Understanding and harnessing the beneficial seed-associated microorganisms may offer new avenues for disease suppression. Management approaches also need to account for potential

shifts in pathogen behavior due to climate change. Enhancing global collaboration on seed health standards, testing protocols, and information sharing is essential for preventing disease spread through trade. Emphasis on agroecological approaches and integrated pest management can reduce reliance on chemical inputs while maintaining crop health. Exploring emerging technologies such as low-pressure plasma treatments and nanotechnology-based approaches may provide additional management tools. Key areas for further research include seed-pathogen-environment interactions, transmission mechanisms, and the development of rapid, field-deployable diagnostic tools.

In conclusion, managing seed-borne pathogens requires a multifaceted approach that combines technological innovation, sustainable practices, and enhanced international cooperation. By addressing these challenges, cooperative work can focus on mitigating the impact of economically important plant pathogens and ensuring global food security.

Types of Seed-borne Pathogens

Seed-borne pathogens can be categorized as fungi, bacteria, viruses, and nematodes. Each plant type has specific characteristics that affect its health.

Fungi

Fungal pathogens are among the most prevalent seed-borne threats to crops, causing diseases such as anthracnose, rust, and smut, which negatively affect the crop yield and quality. For example, maize seeds can carry fungal pathogens such as *Fusarium moniliforme* and *Aspergillus* species, which generate mycotoxins harmful to both plants and humans.^{12,4} However, endophytic fungi can also offer benefits, as some fungal isolates have been found to inhibit the growth of harmful pathogens.⁵

Bacteria

Bacterial pathogens carried by seeds can cause significant diseases that negatively affect germination rate and seed quality. For example, *Pseudomonas syringae* and *Xanthomonas axonopodisare* frequently found in soybean plants, where they hinder seed growth and crop yield.⁶ Certain seed-borne bacteria, such as *Burkholderia plantarii* in rice, are crucial contributors to disease development because of their interactions with environmental factors.⁷

Viruses

Seed-transmitted viruses can be disseminated through nematode vectors, which acquire and transmit viruses, such as the tomato black ring virus (TBRV) and raspberry ringspot virus (RRV) from infected seeds to healthy seedlings. The prevalence of these viruses varies depending on the host plant and environmental conditions, which influence their persistence and spread.¹³

Nematodes

Nematodes are microscopic worms capable of carrying viruses and spreading them through seeds

and soils. For instance, root-knot nematodes affect cucurbit crops by causing root diseases, which can be managed through resistance breeding and grafting.¹⁴ Interactions and specificity between nematodes and other pathogens, such as fungi or bacteria, can intensify crop disease.¹⁵

Common Seed-borne diseases

Seed-borne diseases affect a wide range of crops, including cereals, legumes, vegetables, and other economically important species. Some common major seed-borne diseases in key crop types are listed in Table 1.

Table 1: Some common seed-borne diseases in crops.

Crop Type	Crop	Disease	Pathogen	Symptoms	
Cereal	Maize (Zea Mays)	Anthracnose	<i>Colletotrichum</i>	Stalk discoloration, rot,	
		Stalk Rot	<i>graminicola</i>	lodging, and yield loss.	
		Charcoal Rot	<i>Macrophomina phaseolina</i>	Root and lower stem rot,	
		Aspergillus	<i>Aspergillus flavus</i>	reduced vigor and yield.	
Cereal	Maize (Zea Mays)	Ear and		Kernel rot, aflatoxin	
		Kernel Rot		contamination (health risk)	
		Corn Smut	<i>Ustilago maydis</i>	Galls on various tissues,	
Cereal	Rice	Seed-borne		reduced yield. ⁴	
		Bacterial	<i>Burkholderia plantarii</i>	Affects seed vigor, leads	
Legume	Soybean	Diseases		to bacterial blight or leaf	
		Leaf Spot	<i>Cercospora sojae</i> ,	streak. ⁷	
Legume	Soybean	Diseases	<i>C. kikuchii</i> , <i>Septoria</i>	Leaf spots, premature	
		Leaf Spot	<i>glycines</i>	defoliation, reduced	
Vegetable	Tomato	Fusarium	<i>Fusarium oxysporum</i>	photosynthesis and yield. ⁶	
		Wilt		Wilting, yellowing foliage,	
	Tomato	Early &	<i>Alternaria solani</i> ,	plant death. ¹⁶	
		Late Blight	<i>Alternaria alternata</i> , and	Leaf lesions, leaf spots	
	Eggplant	Leaf spot /	<i>Phytophthora infestans</i>	and rots, significant yield	
		blight	<i>Alternaria alternata</i>	loss.	
	Pepper	Leaf spot			Leaf lesions, leaf spots
				<i>Alternaria alternata</i>	Significant yield and
Cucurbits	Cucurbits	Downy	<i>Pseudoperonospora</i>	quality loss. ¹⁷	
		Mildew	<i>cubensis</i>	Reduced plant growth;	
		Gummy	<i>Didymella bryoniae</i>	physiological &	
		Stem Blight		biochemical changes. ¹⁸	
				Affects foliage, reduces	
				photosynthesis and yields	
				Stem cankers, fruit rot. ¹⁶	

Economically Important	Lentils	Ascochyta Blight	<i>Ascochyta spp.</i>	Leaf spots, stem lesions, pod infection, yield and quality loss
	Chickpeas	Anthracnose Blight	<i>Colletotrichum truncatum</i>	Sunken lesions on pods and stems, seed loss. ¹⁹

The management of these diseases involves integrated pest management practices, including crop rotation, seed treatment and the use of resistant varieties.

Transmission and Infection Mechanisms

Seeds can be infected by pathogens through a variety of methods, posing a major threat to agricultural production, as they can transmit diseases to both young seedlings and fully grown plants. These seeds can serve as vectors for various pathogens, including viruses, bacteria, and fungi.

Infection Mechanisms of Seeds by Pathogenic Microorganisms

Vertical Transmission

Viruses frequently evade plant defence systems and exploit seeds for transmission. This transmission can occur through viable seeds, with viruses entering directly via the embryo or indirectly via the pollen grains or ovules. For instance, viruses such as the zucchini yellow mosaic virus (ZYMV) and pepino mosaic virus (PepMV) can spread through seeds, serving as reservoirs for these viruses and facilitating their dissemination.²⁰⁻²³

Bacterial Invasion

Seeds can serve as reservoirs for bacterial pathogens. Specifically, *Xanthomonas citri* pv. *fuscans* can infiltrate seeds via vascular elements, micropyles, and testa. These bacteria can penetrate seed tissues and effectively utilize the floral route for seed infections.^{24,25}

Seed Microbiome Dynamics

The seed microbiome is integral to its interactions with pathogens. Although pathogenic agents such as *Alternaria brassicicola* can be transmitted through seeds, their interactions with other microbial inhabitants on seeds can influence their transmission rate and facilitate the establishment of pathogen niches within seed tissues.²⁶

Transmission from Seeds to Seedlings and Mature Plants

Seedling Infection

This mode of transmission allows pathogens to bypass plant defenses and gain early access to vulnerable tissues. Viruses such as Zucchini Yellow Mosaic Virus (ZYMV) and bacterial species such as *Xanthomonas* can persist on seeds, lying dormant until conditions favor seed germination and pathogen proliferation. The process of pathogen transmission from seeds to seedlings involves interactions between the pathogen, seeds, and emerging plant tissues. As the seeds absorb water and germinate, the pathogens become metabolically active and rapidly multiply. They can then colonize the developing root system, cotyledons, or primary leaves of seedlings. Early infection can lead to systemic spread throughout plants, resulting in stunted growth, reduced vigor, and decreased yield. Moreover, infected seedlings can serve as sources of inoculum, facilitating pathogen spread to neighboring plants and exacerbating disease outbreaks in agricultural settings.^{22,25}

Epidemiological Implications

Environmental conditions play a crucial role in seed pathogen survival and transmission, while temperature, humidity, and soil composition affect pathogen viability and spread. Stressful abiotic conditions such as drought, extreme temperatures, or nutrient deficiencies can weaken the natural defenses of plants, making them more susceptible to pathogen invasion. When favorable conditions return, these pathogens, which survive during the stress period, can spread rapidly throughout plant populations, leading to increased disease incidence and crop losses. The ability of seed pathogens to persist under adverse conditions and exploit improved environments highlights the importance of understanding environmental factors in plant health and developing resilient varieties with integrated pest management approaches that consider pathogen-host-environment interactions.²⁰

Non-host Seed Transmission

Seeds from non-host plants occasionally harbor these pathogens. Although these seeds may not exhibit symptoms or trigger immune responses, they can facilitate pathogen dissemination, underscoring the intricate nature of the pathogen transmission dynamics via seeds.²⁵

In conclusion, seed-borne pathogen transmission is a multidisciplinary concern affecting plant disease management. Efforts to manage these transmissions include understanding pathogen-host interactions, seed microbiome dynamics, and environmental impacts, which are crucial steps in combating the spread of plant diseases.

Factors Affecting Seed-Borne Diseases

Seed-borne diseases are influenced by various factors including environmental conditions, seed

storage practices, and crop management techniques. Each factor plays a crucial role in exacerbating or mitigating the effects of these diseases on agricultural productivity.

Environmental Conditions

Environmental factors, including temperature and humidity, significantly affect the occurrence and dissemination of seed-borne diseases in plants. Pathogens often thrive under conditions favorable for seed germination and plant growth, resulting in an increased incidence of disease when such conditions are present.⁴ Elevated humidity levels and moderate temperatures are particularly conducive to the proliferation of numerous fungal and bacterial pathogens, thereby increasing the risk of seed-borne diseases.²⁷ Environmental conditions are mentioned in Table 2.

Table 2: Optimal temperature and relative humidity requirements of selected plant pathogens, along with their environmental preferences, highlighting conditions that favour their growth, survival, and infection potential.

Pathogen	Optimal Temperature	Relative Humidity	Environmental Preference Requirement
<i>Colletotrichum graminicola</i>	Warm	High	Typical of many fungal pathogens; thrives in moist, warm climates. ²⁸
<i>Macrophomina phaseolina</i>	Warm	Low	Prefers dry conditions; common in warmer climates. ²⁹
<i>Aspergillus flavus</i>	Hot	Low	Produces aflatoxins; thrives in hot, dry, drought-prone areas. ³⁰
<i>Ustilago maydis</i>	Moderate	High	Corn smut pathogen; optimal spore germination in humid conditions. ³¹
<i>Burkholderia plantarii</i>	Wide range	High	Bacterial pathogen; humidity essential but temperature tolerance is broad. ³²
<i>Cercospora sojina</i>	Variable	High	High moisture boosts virulence; common in humid regions. ³³
<i>Cercospora kikuchii</i>	Variable	High	Similar to <i>C. sojina</i> ; slight variation in temperature preference. ³³
<i>Septoria glycines</i>	Stable moderate	High	Prefers consistent temperatures; reduced activity with extreme fluctuations. ³⁴
<i>Fusarium oxysporum</i>	Warm	Moderate High	Adaptable to various climates; prefers moist soils. ³⁵

<i>Alternaria solani</i>	Moderate	High	High humidity aids spore dispersal; causes early blight. ³³
<i>Alternaria alternata</i>	Moderate	High	Similar to <i>A. solani</i> ; favors humid conditions for infection. ³³
<i>Phytophthora infestans</i>	Cool	High	Late blight pathogen; thrives in cool, wet conditions. ²⁹
<i>Pseudoperonospora cubensis</i>	Cool	High	Downy mildew pathogen; rapid spread in cool, humid conditions. ³²
<i>Didymella bryoniae</i>	Warm	High	Infects cucurbits; needs warm, wet conditions. ³⁰
<i>Ascochyta spp.</i>	Moderate–Warm	High	Fungal pathogen; moisture essential for infection cycle. ³⁶
<i>Colletotrichum truncatum</i>	Moderate–Warm	High	Requires humid environments for growth and infection. ³⁶

Seed Storage Practices

Effective seed storage is essential for reducing the incidence of seed-borne diseases. By maintaining the seeds under controlled temperature and humidity conditions, the risk of pathogen proliferation can be minimized. Additionally, seed treatment and coating with compounds such as chitosan are beneficial for improving the seed quality. Chitosan serves as a seed coating that not only provides a physical barrier against pathogens but also induces plant defence mechanisms, thereby decreasing susceptibility to infection.³⁷

Crop Management Techniques

Crop management practices and seed treatment play crucial role in influencing the dynamics of seed-borne diseases. Innovative seed treatments, such as the application of biocontrol agents and natural compounds, have been developed to shield seeds and seedlings from pathogen attacks, thereby minimizing reliance on synthetic pesticides.³⁸ Furthermore, incorporating seed endophytes into seed treatment offers the dual advantages of disease suppression and plant growth promotion. Some studies have shown that endophytes isolated from seeds can effectively protect against and suppress seed-borne pathogens.⁵

These factors highlight the complexity of managing seed-borne diseases, necessitating a comprehensive approach that integrates environmental management, advanced seed treatment and holistic crop management techniques. Understanding these interactions will aid in the development of effective

strategies to mitigate the adverse effects of seed-borne diseases on crop health and yields.

Detection and diagnosis methods

Methods for the detection and diagnosis of seed-borne pathogens are essential to maintain seed health and prevent disease dissemination. These methods are categorized into traditional and advanced techniques, each with unique context-dependent advantages and limitations.

Traditional Methods

Visual Inspection and Blotter Tests

Traditional methods, such as visual inspection and blotter tests, are the initial approaches for identifying seed-borne pathogens. Visual inspection entails scrutinizing seeds for evident signs of infection, which is effective for visible pathogens but fails to detect asymptomatic infections in seeds. This tests involve incubating seeds on moist blotting paper to facilitate pathogen growth and identification. Although these methods are straightforward and cost-effective, they are labor-intensive and may lack the sensitivity required to detect low levels of infestation or asymptomatic pathogens.³⁹

Agar Plating

Agar plating is a method used to cultivate and identify fungi in seed samples using media such as Potato Dextrose Agar (PDA). This technique is particularly effective for detecting fungal pathogens such as *Aspergillus* and *Fusarium* species. However, this is a time-consuming process and non-culturable pathogens may not be identified.⁴

Advanced Techniques

Polymerase Chain Reaction (PCR)

PCR has significantly advanced the detection of seed-borne pathogens, owing to its high sensitivity and specificity. This facilitates the amplification of pathogen DNA from seeds, even in the presence of inhibitory compounds at low pathogen concentrations. Although PCR-based methods require high-quality DNA extraction, techniques such as Bio-PCR and immunomagnetic separation have improved their effectiveness. PCR can be integrated with other technologies, such as DNA chip technology for rapid and specific pathogen detection.⁴⁰

Enzyme-Linked Immunosorbent Assay (ELISA)

ELISA is a serological test that uses antibodies to identify specific pathogenic proteins in a sample. It offers a quantitative assessment of the presence of pathogens, and is advantageous for high-throughput screening. However, this method requires specific antibodies for each pathogen and may not be able to detect novel or less well-characterized pathogens.³⁹

Next-Generation Sequencing (NGS) and CRISPR/Cas-based Methods

NGS facilitates comprehensive profiling of seed microbiomes, enabling the detection of both known and novel pathogens. CRISPR/Cas-based methods are innovative approach characterized by high sensitivity and specificity without the need for extensive equipment. Although these technologies hold significant promise, further development and cost reduction are required for their routine application.^{41,42}

Hyperspectral Imaging (HSI)

When integrated with artificial intelligence, HIS enables the precise differentiation between healthy and infected seeds through spectral signatures. Although this method shows promise for high-throughput screening, it entails considerable costs and requires interdisciplinary collaboration to standardize and validate the protocols.⁴²

By integrating traditional and advanced methods, the detection and diagnosis of seed-borne pathogens

can be significantly improved, thereby facilitating effective disease management and ensuring the safety and quality of agricultural seed stock.

Management and control strategies

Effective management and control of plant diseases necessitate a multifaceted approach that incorporates seed treatments, cultural practices, the use of resistant varieties, and integration strategies.

Seed Treatments or priming

Seed treatment serves as a crucial initial defence against soil-borne diseases and pests. These treatments can be categorized as chemical, biological, or physical treatments. Chemical seed treatments involve the use of fungicides or insecticides to shield the seeds from pathogens and pests during germination. Biological treatments employ microorganisms, such as beneficial fungi or bacteria, to suppress pathogen growth. Physical treatments may include heat treatment, which eradicates pests without the use of chemicals.⁴³ Details of chemicals used for seed treatment is given in Table 3.

Cultural Practices

Cultural practices play a crucial role in the management of plant diseases by disrupting the life cycle of pathogens. Techniques such as crop rotation, sanitation, proper irrigation, and the use of disease-free seeds can effectively prevent the spread of diseases and reduce the pathogen load in the environment. These practices contribute to sustainable agriculture by minimizing dependence on chemical inputs.⁴⁵

Resistant Varieties

The development and utilization of plant varieties resistant to specific pathogens are essential for sustainable disease management. This strategy reduces dependence on chemical pesticides and can facilitate the long-term control of plant diseases. Techniques in genetic engineering and traditional breeding have been employed to create resistant varieties capable of withstanding pathogen attack, thereby enhancing agricultural productivity and sustainability.⁴⁶

Table 3: Chemicals used for seed priming in crop applications, their benefits, main purpose, and mode of action.

Chemical	Crop Used for Seed Priming	Benefits	Mode of Action	main purpose
Salicylic acid	Bread wheat cultivars	Improved germination, and yield especially under saline conditions	Acts as signaling molecule in systemic acquired resistance (SAR); enhances antioxidant enzymes; regulates ion uptake under stress	Boosts plant immunity; contributes to integrated pest management. ⁴⁴
Thiourea	Capsicum	Improved tolerance to cold and salt stress	Scavenges reactive oxygen species (ROS); improves osmotic adjustment; stimulates antioxidant defense	Higher germination rates and better seedling survival. ⁴⁴
Hydrogen peroxide	Capsicum	Improved tolerance to cold and salt stress	Functions as signaling molecule; induces antioxidant enzymes; promotes seed metabolism during germination	Priming for stress resistance. ⁴⁴
Potassium phosphate	Maize	Enhanced germination and seedling vigor; reduced phytate content	Supplies phosphorus and potassium; induces systemic resistance via defense pathway activation.	Enhance seedling vigor and nutrition. ⁴⁴
Acetylsalicylic acid	Wheat, tomato, rice	Enhances disease resistance, improves seedling vigor	Converted into salicylic acid; may trigger defense-related gene expression	Enhance disease resistance and seedling vigor

Integrated Disease Management (IDM)

IDM encompasses the application of multiple strategies for sustainably managing plant diseases. This approach integrates chemical, biological, and cultural controls to establish a comprehensive defence system against pests and diseases in crops. The IDM mitigates the environmental impact of agriculture by reducing chemical use and encouraging alternative control strategies.

Advancements in precision agriculture technologies, such as drones and remote sensing, facilitate the early detection and management of disease outbreaks, thereby enhancing the efficacy of IDM.^{47,48}

Incorporating a diverse set of strategies can significantly enhance disease management, promote environmental sustainability, and increase the agricultural output.

Impact on seed quality and crop yield

Seed quality is a critical determinant of germination rate, seedling vigor, crop productivity, and yield loss. Seed quality is influenced by a range of factors including genetic characteristics, health, and viability, all of which affect crop performance.

Effects on Germination and Seedling Vigor

Seed quality plays a crucial role in determining germination rate and seedling vigor. High-quality seeds generally exhibit superior germination rates, which results in robust seedling growth. This is attributed to the preservation of the integrity of macromolecular structures, such as DNA, which are

essential for subsequent cell division and growth. Maintaining genome integrity during the initial stages of seed germination reduces the risk of growth inhibition and mutations, thereby enhancing seedling vigor.⁴⁹ Furthermore, seed priming techniques, such as optical seed priming, have been shown to enhance germination rates by up to 180% compared with controls, as demonstrated in cotton seeds. This method improves the germination process by utilizing various light spectra to precondition the seeds, resulting in more vigorous seedlings.⁵⁰ Advanced seed priming techniques along with its purpose and effects are given in Table 4.

Table 4: Advanced seed-priming techniques and bio-based methods for improving germination, stress resilience, and disease resistance in plants.

Technique / Method	Example / Source	Main Purpose	Mechanism / Effect
Bacterial Metabolites	Metabolites from <i>Bacillus gaemokensis</i>	Induce plant immunity; reduce bacterial diseases	Activates defense pathways (salicylic acid, ethylene, jasmonic acid); increases yield. ⁵¹
Cell Cycle Inhibitors	Mimosine, aphidicolin, hydroxyurea, oryzalin	Enhance seed storability	Suppress seed deterioration during priming. ⁵²
Silicon Compounds	Calcium silicate	Alleviate salt stress in lettuce	Enhances antioxidant responses; improves germination. ⁵³
Chitosan Nanoparticles	Chitosan-based nanoformulation	Alleviate salinity stress in rice	Boosts germination potential & vigor; enhances biochemical responses. ⁵⁴
Wood Distillate	Bio-based distillate from wood	Eco-friendly germination enhancer	Improves germination & seedling growth (chickpea, lettuce, basil). ⁵⁵
Cold Plasma	Plasma-treated seeds	Improve germination & seedling establishment	Enhances nutrient uptake & antioxidant defense (e.g., cumin). ⁵⁶

These chemicals and methods highlight the diverse approaches available for improving seed germination and building plant immunity, indicating a broad potential for application in agriculture to address environmental stress.

Influence on Crop Productivity and Yield Loss

Seed vigor directly influences crop yield through plant performance and indirectly through plant population density. Studies have shown that

seed vigor significantly affects crop yield during the vegetative and early reproductive stages of development. However, in crops harvested at full reproductive maturity, the influence of seed vigor decreases as seed yield is not closely tied to vegetative growth.⁵⁷ Seed-borne pathogens reduce seed germination and vigor, leading to yield losses of 15–90%, highlighting the need for seed health maintenance.³

Environmental factors affecting seed quality and crop yield. Elevated CO₂ levels increase chickpea seed yield by 11-18% while altering nutritional composition, although seed germination remains unaffected.⁵⁸

Seed quality determines crop germination, vigor and yield. High-quality seeds enhance germination and seedling vigor, thereby positively affecting the productivity. Methods such as seed priming and the maintenance of genome integrity are vital for improving seed quality and crop yield, thereby contributing to sustainable crop production.

Seed health testing and certification

Testing and certifying seed health is essential for maintaining seed quality and safety in international commerce, as dictated by global standards and regulations. The significance of this certification is increasingly acknowledged in its role in facilitating worldwide trade by fulfilling phytosanitary requirements and enhancing trust among trading partners in the global market.

International Standards and Regulations

Seed health testing and certification require compliance with stringent international standards aimed at the detection and management of seed-borne pathogens, as delineated by research innovations. These standards are subject to continuous evolution and incorporate advanced detection methodologies, such as PCR-based techniques, to ensure reliable results.³⁹ Regulations are frequently informed by pest risk analysis outcomes to incorporate scientific advancements and facilitate the safe and transboundary movement of seeds. This approach helps circumvent trade barriers and fosters the harmonization of phytosanitary measures on a global scale.

Importance in Global Trade

Health certifications play a crucial role in the international seed trade by facilitating market access by adhering to the phytosanitary requirements of importing countries. These certifications function as quality assurance mechanisms, protecting agricultural production chains from potential seed-borne disease outbreaks and bolstering the confidence of trade partners in seed products.³⁹ Furthermore, certification can act as a trade facilitator rather than a barrier, enhancing export

competitiveness, especially from developing to developed nations, by raising the standards of seed quality and reliability.

Seed health testing and certification help to protect both farmers and the environment. They have also supported strong international trade by ensuring product quality and safety. Although challenges in standardizing global practices remain, current systems help create a more connected and robust global seed market.

Challenges in Managing Seed-Borne Diseases

The management of seed-borne diseases poses considerable challenges, primarily because of the emergence of new pathogens, evolution of resistance, impact of climate change, and limitations inherent to current detection and control methodologies.

A Significant challenge is the emergence of novel pathogens and their resistance to treatment. The expansion of the global seed market has facilitated the international dissemination of seed-borne pathogens, necessitating innovations in pathogen detection and management.⁴² This includes the development of advanced techniques, such as polymerase chain reaction (PCR)-based methods and hyperspectral imaging, which offer high accuracy in pathogen detection but require substantial standardization and validation.^{42,39} Emerging technologies, such as low-pressure plasma treatments, show promise in controlling specific pathogens by damaging their cell structures.⁵⁹

Climate change adds complexity to management efforts by affecting the adaptation and spread of pathogens. Fluctuations in climate conditions can impact infection success rates and alter the behavior of diseases that originate from seeds and soil.⁶⁰ Shifts in weather patterns may cause diseases to emerge in new areas where they were previously absent, posing challenges to the current management strategies.

Detection and control methodologies face both technical and operational constraints. Although advanced technologies, such as hyperspectral imaging and nucleic acid-based detection methods, represent the forefront of pathogen identification, they are associated with significant costs and require

interdisciplinary collaboration.⁴² The standardization of these methodologies is essential for their broad adoption and efficacy in seed health testing.³⁹ Furthermore, although seed treatments can effectively eradicate pathogens, their environmental impacts warrant careful consideration, especially concerning traditional chemical treatments that may result in ecological imbalances.^{61,62}

Moreover, the significance of biosecurity in the context of the international seed trade should not be underestimated. Despite the biosecurity risks associated with seed-borne pathogens, trade regulations frequently lack stringent controls, thereby increasing the likelihood of introducing pathogens into new environments.⁴⁵ This issue is further compounded by the existing gaps in understanding the role and transmission potential of fungal pathogens linked to seeds.⁶³

To effectively address these challenges, adopting a comprehensive strategy that includes technological innovations, sustainable methods, and enhanced international regulations for managing seed-borne diseases is essential.

Discussion

This comprehensive review examined the economic and environmental implications of seed-borne diseases in agriculture. Seed-borne pathogens, including fungi, bacteria, viruses, and nematodes, significantly affect seed quality, germination rate, and crop yield, leading to substantial economic losses in agriculture. This review discusses the transmission and infection mechanisms of these pathogens, factors affecting their spread, detection and diagnosis methods, seed health testing and certification, and the challenges associated with the management of seed-borne diseases. This review highlights the importance of adopting a comprehensive strategy that includes technological innovations, sustainable methods, and enhanced international regulations for the effective management of seed-borne diseases to ensure sustainable crop production and food security.

Conclusion

This comprehensive review examines the impact of seed-borne pathogens on crop production and food security. These pathogens significantly

compromise seed quality, germination rates, and crop yield, leading to substantial economic losses. The transmission mechanisms of these diseases are complex, and environmental factors pose ongoing challenges. Although advanced detection methods have improved pathogen identification, further development is necessary. Seed health testing and certification are critical; however, international standards remain unharmonized. Thus, effective management requires an integrated approach. Although emerging technologies are promising, further research is required. Climate change further complicates these issues. A multifaceted strategy that encompasses technological innovation, sustainable practices, enhanced biosecurity, and international regulatory cooperation is essential. This approach could safeguard seed health, improve productivity, and enhance food security.

Acknowledgement

The authors extend their sincere appreciation to the Tree Ambulance Project for their invaluable technical support during the preparation of this manuscript. We also express our gratitude to the faculty and staff of RKDF University, Ranchi, for their guidance, encouragement, and provision of institutional resources. The collaborative efforts and insights of all team members significantly contributed to the successful completion of this review.

Funding sources

This research was funded by Central Coalfield Ltd. (CCL), CSR Ranchi as part of the Tree Ambulance Project. Grant approval letter no. GM (SD & CSR)/54 dt. 31.01.2023.

Conflict of Interest

The authors do not have any conflict of interest.

Data Availability Statement

This statement does not apply to this article

Ethics Statement

This research did not involve human participants, animal subjects, or any material that requires ethical approval.

Informed Consent Statement

This study did not involve human participants, and therefore, informed consent was not required.

Permission to reproduce material from other sources

Not Applicable

Author Contributions

- **Barkha Kachhap:** Conceptualization, Literature Search, Writing - Original Draft

- **Sneha Pandey:** Methodology, Critical Review, Writing - Review & Editing
- **Mainak Banerjee:** Data Synthesis, Visualization, Writing - Review & Editing
- **Amit Kumar Pandey:** Supervision, Project Administration, Final Approval
- **Nilu Kumari:** Critical Review

References

1. Waldron A, Malhi Y, Miller DC, Seddon N, Garrity D, Girardin C. Agroforestry Can Enhance Food Security While Meeting Other Sustainable Development Goals. *Tropical Conservation Science*. 2017;10(1):194008291772066. <https://doi.org/10.1177/1940082917720667>
2. Albahri G, Baydoun E, Nasser M, *et al.* Enhancing Essential Grains Yield for Sustainable Food Security and Bio-Safe Agriculture through Latest Innovative Approaches. *Agronomy*. 2023;13(7):1709. <https://doi.org/10.3390/agronomy13071709>
3. Gebeyaw M. Review on: Impact of Seed-Borne Pathogens on Seed Quality. *American Journal of Plant Biology*. 2020;5(4):77. <https://doi.org/10.11648/j.ajpb.20200504.11>
4. Rehman FU, Adnan M, Kalsoom M, *et al.* Seed-Borne Fungal Diseases of Maize (*Zea mays* L.): A Review. *Jurnal Agroteknologi dan Perkebunan*. 2021;4(1):43-60. <https://doi.org/10.36490/agri.v4i1.123>
5. Kim J, Jeon J, Ahn SH, *et al.* Culturable Endophytes Associated with Soybean Seeds and Their Potential for Suppressing Seed-Borne Pathogens. *The Plant Pathology Journal*. 2022;38(4):313-322. <https://doi.org/10.5423/ppj.oa.05.2022.0064>
6. Kim J, Ahn SH, Choi S, Jung HW, Jeon J, Yang JS. Plant Protective and Growth Promoting Effects of Seed Endophytes in Soybean Plants. *The Plant Pathology Journal*. 2023;39(5):513-521. <https://doi.org/10.5423/ppj.oa.06.2023.0091>
7. Matsumoto H, Qiao K, Chen S, *et al.* Bacterial seed endophyte shapes disease resistance in rice. *Nature plants*. 2021;7(1):60-72. <https://doi.org/10.1038/s41477-020-00826-5>
8. Agarwal V, Sinclair J. *Principles of Seed Pathology* (1987). crc; 2017. <https://doi.org/10.1201/9780203710814>
9. Xhemali B, Giovanardi D, Biondi E, Stefani E. Tomato and Pepper Seeds as Pathways for the Dissemination of Phytopathogenic Bacteria: A Constant Challenge for the Seed Industry and the Sustainability of Crop Production. *Sustainability*. 2024;16(5):1808. <https://doi.org/10.3390/su16051808>
10. Barret M, Darrasse A, Guimbaud J, Jacques M. Plant microbiota affects seed transmission of phytopathogenic microorganisms. *Molecular Plant Pathology*. 2016;17(6):791-795. <https://doi.org/10.1111/mpp.12382>
11. Lamichhane JR, Barbetti MJ, You MP, Aubertot JN, Debaeke P, Steinberg C. Abiotic and biotic factors affecting crop seed germination and seedling emergence: a conceptual framework. *Plant and Soil*. 2018;432(1-2):1-28. <https://doi.org/10.1007/s11104-018-3780-9>
12. Goko ML, Rugare JT, Murimwa JC, Ngadze E, Gasura E. Identification and Characterisation of Seed-Borne Fungal Pathogens Associated with Maize (*Zea mays* L.). *International Journal of Microbiology*. 2021;2021(12):1-11. <https://doi.org/10.1155/2021/6702856>
13. Murrant AF, Lister RM. Seed-transmission in the ecology of nematode-borne viruses. *Annals of Applied Biology*. 1967;59(1):63-76. <https://doi.org/10.1111/j.1744-7348.1967.tb04417.x>
14. Ayala-Doñas A, Verdejo-Lucas S, Talavera-Rubia M, Cara-García MD. Management of Soil-Borne Fungi and Root-Knot Nematodes in Cucurbits through Breeding for Resistance and Grafting. *Agronomy*. 2020;10(11):1641. <https://doi.org/10.3390/agronomy10111641>
15. Riley IT, McKay AC. Specificity of the Adhesion of Some Plant Pathogenic Micro-Organisms To the Cuticle of Nematodes in the Genus *Anguina* (Nematoda: Anguinidae).

- Nematologica*. 1990;36(1-4):90-103. <https://doi.org/10.1163/002925990x00068>
16. Tripathi AN, Maurya S, Pandey KK, Behera TK. Global Scenario of Vegetable Fungal Diseases. *Vegetable Science*. 2024;51(Special Is):54-65. <https://doi.org/10.61180/vegsci.2024.v51.spl.06>
 17. Kaniyassery A, Thorat SA, Kiran KR, Murali TS, Muthusamy A. Fungal diseases of eggplant (*Solanum melongena* L.) and components of the disease triangle: A review. *Journal of Crop Improvement*. 2022;37(4):543-594. [doi:10.1080/15427528.2022.2120145](https://doi.org/10.1080/15427528.2022.2120145)
 18. Soliman SA, Abdelhameed RE, Metwally RA. In vivo and In vitro evaluation of the antifungal activity of the PGPR *Bacillus amyloliquefaciens* RaSh1 (MZ945930) against *Alternaria alternata* with growth promotion influences on *Capsicum annuum* L. plants. *Microb Cell Fact*. 2023;22(1). [doi:10.1186/s12934-023-02080-8](https://doi.org/10.1186/s12934-023-02080-8)
 19. Krupinsky JM, Turkington TK, McMullen MP, Gossen BD, Bailey KL. Managing Plant Disease Risk in Diversified Cropping Systems. *Agronomy Journal*. 2002;94(2):198-209. <https://doi.org/10.2134/agronj2002.1980>
 20. Gutiérrez-Sánchez Á, Cobos A, López-Herranz M, Canto T, Pagán I. Environmental conditions modulate plant virus vertical transmission and survival of infected seeds. *Phytopathology*. 2023;113(9):1773-1787. <https://doi.org/10.1094/phyto-11-22-0448-v>
 21. Escalante C, Balkcom KS, Jacobson A, *et al.* Plant virus transmission during seed development and implications to plant defense system. *Frontiers in Plant Science*. 2024;15. <https://doi.org/10.3389/fpls.2024.1385456>
 22. Simmons HE, Bothe-Goralczyk MA, Holmes EC, Gildow FE, Stephenson AG. Experimental Verification of Seed Transmission of Zucchini yellow mosaic virus. *Plant Disease*. 2011;95(6):751-754. <https://doi.org/10.1094/pdis-11-10-0843>
 23. Hanssen IM, Pagán I, Pospieszny H, *et al.* Seed transmission of Pepino mosaic virus in tomato. *European Journal of Plant Pathology*. 2009;126(2):145-152. <https://doi.org/10.1007/s10658-009-9528-x>
 24. Darrasse A, Jacques MA, Cesbron S, Barret M, Compant S. Niches and routes of transmission of *Xanthomonas citri* pv. *fuscans* to bean seeds. *Plant and Soil*. 2017;422(1-2):115-128. <https://doi.org/10.1007/s11104-017-3329-3>
 25. Darrasse A, Durand K, Brisset MN, Boureau T, Darsonval A, Jacques MA. Transmission of plant-pathogenic bacteria by nonhost seeds without induction of an associated defense reaction at emergence. *Applied and Environmental Microbiology*. 2010;76(20):6787-6796. <https://doi.org/10.1128/aem.01098-10>
 26. Torres-Cortés G, Briand M, Compant S, *et al.* Differences in resource use lead to coexistence of seed-transmitted microbial populations. *Scientific Reports*. 2019;9(1). <https://doi.org/10.1038/s41598-019-42865-9>
 27. Fiers M, Edel-Hermann V, Chatot C, Steinberg C, Le Hingrat Y, Alabouvette C. Potato soil-borne diseases. A review. *Agronomy for Sustainable Development*. 2011;32(1):93-132. <https://doi.org/10.1007/s13593-011-0035-z>
 28. AP, VM. A Review on Soil and Phytomicrobiome for Plant Disease Management. *IJECC*. 2023;13(10):2890-2904. [doi:10.9734/ijecc/2023/v13i102955](https://doi.org/10.9734/ijecc/2023/v13i102955)
 29. Elad Y, Pertot I. Climate Change Impacts on Plant Pathogens and Plant Diseases. *Journal of Crop Improvement*. 2014;28(1):99-139. [doi:10.1080/15427528.2014.865412](https://doi.org/10.1080/15427528.2014.865412)
 30. Leisner CP, Sanz-Saez A, Potnis N. Crosstalk and trade-offs: Plant responses to climate change-associated abiotic and biotic stresses. *Plant Cell & Environment*. 2023;46(10):2946-2963. [doi:10.1111/pce.14532](https://doi.org/10.1111/pce.14532)
 31. Yáñez-López R. The effect of climate change on plant diseases. *Afr J Biotechnol*. 2012;11(10). [doi:10.5897/ajb10.2442](https://doi.org/10.5897/ajb10.2442)
 32. Santoyo G, Hernández-Salmerón J, Hernández-León R, Hernández-Pacheco C. The role of abiotic factors modulating the plant-microbe-soil interactions: toward sustainable agriculture. A review. *Span j agric res*. 2017;15(1):e03R01. [doi:10.5424/sjar/2017151-9990](https://doi.org/10.5424/sjar/2017151-9990)
 33. Douglas KO, Payne K, Sabino-Santos G, Agard J. Influence of Climatic Factors on

- Human Hantavirus Infections in Latin America and the Caribbean: A Systematic Review. *Pathogens*. 2021;11(1):15. doi:10.3390/pathogens11010015
34. Palmer JS, West HM, Avery LM, Hough RL. A review of the abundance, behaviour and detection of clostridial pathogens in agricultural soils. *European J Soil Science*. 2019;70(4):911-929. doi:10.1111/ejss.12847
35. Ayhan DH, Abbondante S, Martínez-Soto D, *et al.* Virulence of *Fusarium oxysporum* strains causing corneal or plant disease is associated with their distinct accessory chromosomes. bioRxiv : the preprint server for biology. Published online April 11, 2025. doi:10.1101/2024.05.23.595639
36. Casas AT. Influence of Temperature, Wetness Period, Plant Age, and Inoculum Concentration on Infection and Development of *Ascochyta* Blight of Chickpea. *Phytopathology*. 1992;82(5):589. doi:10.1094/phyto-82-589
37. Orzali L, Corsi B, Riccioni L, Forni C. Chitosan in Agriculture: A New Challenge for Managing Plant Disease. In: institute for new technologies; 2017. <https://doi:10.5772/66840>
38. Mourni M, Brodal G, Romanazzi G. Recent innovative seed treatment methods in the management of seedborne pathogens. *Food Security*. 2023;15(5):1365-1382. <https://doi:10.1007/s12571-023-01384-2>
39. Munkvold GP. Seed Pathology Progress in Academia and Industry. *Annual Review of Phytopathology*. 2009;47(1):285-311. <https://doi:10.1146/annurev-phyto-080508-081916>
40. Walcott RR. Detection of Seedborne Pathogens. *HortTechnology*. 2003;13(1):40-47. <https://doi:10.21273/horttech.13.1.0040>
41. Wang X, Shang X, Huang X. Next-generation pathogen diagnosis with CRISPR/Cas-based detection methods. *Emerging Microbes & Infections*. 2020;9(1):1682-1691. <https://doi:10.1080/22221751.2020.1793689>
42. Ferreira L da C, Quezado-Duval AM, Jorge LA de C, Carvalho ICB, Rossato M. Hyperspectral imaging for the detection of plant pathogens in seeds: recent developments and challenges. *Frontiers in Plant Science*. 2024;15. <https://doi:10.3389/fpls.2024.1387925>
43. Cook RJ. Biological control and holistic plant-health care in agriculture. *American Journal of Alternative Agriculture*. 1988;3(2-3):51-62. <https://doi:10.1017/s0889189300002186>
44. Massimi M. Crossroads of Seed Science and Agricultural Innovation. *Res J Seed Sci*. 2025;18(1):1-2. doi:10.3923/rjss.2025.01.02
45. Khan SM, Ahmad S, Ejaz S, Bukhari SAH, Nawaz A, Ali S. Integrated Pest and Disease Management for Better Agronomic Crop Production. In: *springer singapore*; 2019:385-428. https://doi:10.1007/978-981-32-9783-8_19
46. Saberi Riseh R, Gholizadeh Vazvani M. Unveiling Methods to Stimulate Plant Resistance against Pathogens. *Frontiers in bioscience (Landmark edition)*. 2024;29(5):188. <https://doi:10.31083/j.fbl2905188>
47. Makwarela TG, Seoraj-Pillai N, Nangammbi TC. Tick Control Strategies: Critical Insights into Chemical, Biological, Physical, and Integrated Approaches for Effective Hard Tick Management. *Veterinary sciences*. 2025;12(2):114. <https://doi:10.3390/vetsci12020114>
48. Daughtrey ML, Benson DM. Principles of Plant Health Management for Ornamental Plants. *Annual Review of Phytopathology*. 2005;43(1):141-169. <https://doi:10.1146/annurev.phyto.43.040204.140007>
49. Waterworth WM, Bray CM, West CE. The importance of safeguarding genome integrity in germination and seed longevity. *Journal of Experimental Botany*. 2015;66(12):3549-3558. <https://doi:10.1093/jxb/erv080>
50. Atta BM, Saleem M, Sarwar G, Farooq A, Abro S, Rizwan M. Enhancement of germination and yield of cotton through optical seed priming: Lab. and diverse environment studies. *PLOS ONE*. 2023;18(7):e0288255. <https://doi:10.1371/journal.pone.0288255>
51. Song GC, Ryu CM, Choi HK, Choi JS, Kim YS. Seed defense bioprimering with bacterial cyclodipeptides triggers immunity in cucumber and pepper. *Sci Rep*. 2017;7(1). doi:10.1038/s41598-017-14155-9
52. Sano N, Seo M. Cell cycle inhibitors improve seed storability after priming treatments. *J Plant Res*. 2019;132(2):263-271. doi:10.1007/s10265-018-01084-5
53. Alves RDC, Oliveira FDAD, Checchio MV, *et al.* Salt stress alleviation by seed priming with silicon in lettuce seedlings: an

- approach based on enhancing antioxidant responses. *Bragantia*. 2020;79(1):19-29. doi:10.1590/1678-4499.20190360
54. Soni AT, Rookes JE, Arya SS. Chitosan Nanoparticles as Seed Priming Agents to Alleviate Salinity Stress in Rice (*Oryza sativa* L.) Seedlings. *Polysaccharides*. 2023;4(2):129-141. doi:10.3390/polysaccharides4020010
55. Maresca V, Corrêa A, Vannini A, *et al.* Wood Distillate Enhances Seed Germination of Chickpea, Lettuce, and Basil. *Applied Sciences*. 2024;14(2):631. doi:10.3390/app14020631
56. Rasooli Z, Barzin G, Mahabadi TD, Entezari M. Stimulating effects of cold plasma seed priming on germination and seedling growth of cumin plant. *South African Journal of Botany*. 2021;142:106-113. doi:10.1016/j.sajb.2021.06.025
57. Tekrony DM, Egli DB. Relationship of Seed Vigor to Crop Yield: A Review. *Crop Science*. 1991;31(3):816-822. https://doi:10.2135/cropsci1991.0011183x003100030054x
58. Lamichaney A, Katiyar PK, Singh NP, Tewari K, Basu PS. Effect of elevated carbon-dioxide on plant growth, physiology, yield and seed quality of chickpea (*Cicer arietinum* L.) in Indo-Gangetic plains. *Physiology and Molecular Biology of Plants*. 2021;27(2):251-263. https://doi:10.1007/s12298-021-00928-0
59. Nishioka T, Okada K, Mishima T, *et al.* Low-Pressure Plasma Application for the Inactivation of the Seed-borne Pathogen *Xanthomonas campestris*. *Biocontrol Science*. 2016;21(1):37-43. https://doi:10.4265/bio.21.37
60. An YN, Murugesan C, Choi H, Kim KD, Chun SC. Current Studies on Bakanae Disease in Rice: Host Range, Molecular Identification, and Disease Management. *Mycobiology*. 2023;51(4):195-209. https://doi:10.1080/12298093.2023.2241247
61. Dutta P, Kaman PK, Mallik M, *et al.* Nanotechnological approaches for management of soil-borne plant pathogens. *Frontiers in Plant Science*. 2023;14. https://doi:10.3389/fpls.2023.1136233
62. Afzal A, Hassaan MA, Abbas A, Ahmad A, Mushtaq S. Enhancing Agricultural Sustainability in Pakistan: Addressing Challenges and Seizing Opportunities through Effective Plant Disease Management. *Plant Protection*. 2023;7(2):341-350. https://doi:10.33804/pp.007.02.4595
63. Franić I, Prospero S, Vettraino AM, *et al.* The Biosecurity Risks of International Forest Tree Seed Movements. *Current Forestry Reports*. 2023;10(2):89-102. https://doi.org/10.1007/s40725-023-00211-3